ANALYSIS OF EUROPAN CYCLOID MORPHOLOGY AND IMPLICATIONS FOR FORMATION MECHANISMS. S. T. Marshall and S. A. Kattenhorn, Department of Geological Sciences, University of Idaho, Moscow, ID 83844-3022. (mars0776@uidaho.edu; simkat@uidaho.edu)

Introduction: Europa's highly fractured crust has been shown to contain features with a range of differing morphologies [1,2]. Most lineaments on Europa are believed to have initiated as cracks, although the type of cracking (e.g. tensile vs. shear) remains unclear and may vary for different morphologies. Arcuate lineaments, called cycloids or flexi, have been observed in nearly all imaged regions of Europa and have been modeled as tensile fractures that were initiated in response to diurnal variations in tides [3,4]. Despite this hypothesis about the formation mechanism, there have been no detailed analyses of the variable morphologies of cycloids. We have examined Galileo images of numerous locations on Europa to develop a catalog of the different morphologies of cycloids. This study focuses on variations in morphology along individual cycloid segments and differences in cusp styles between segments, while illustrating how morphologic evidence can help unravel formation mechanisms. In so doing, we present evidence for cycloid cusps forming due to secondary fracturing during strike-slip sliding on pre-existing cycloid segments.

What Qualifies a Cycloid: A cycloid (Fig. 1) is defined as an arcuate fracture that contains at least two segments and one cusp. Cycloids have previously been noted to be variably manifested as fractures, double ridges, and smooth bands [3-5].

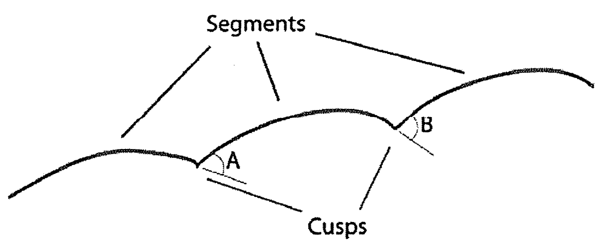

Figure 1. A cartoon of a typical cycloid consisting of segments and cusps with, in this case, differing cusp angles A and B.

Previous Models: Previously, cycloids were interpreted to have formed by thrust faulting [5] or as a result tensile fracturing in a diurnal stress field [3,6]. The diurnal model follows from rotation of principal tidal stress orientations during each Europan day (counter-clockwise in the northern hemisphere and clockwise in the southern hemisphere) [3]. In this model, cycloids are interpreted to be tensile fractures which form perpendicular to the maximum tensile stress and grow in a curved path following the rotating stress field. This implies the cycloid cartooned in Fig. 1 would have propagated towards the left in the northern hemisphere and towards the right in the southern hemisphere. This model agrees remarkably well with the distribution of cycloidal features on Europa [3,6].

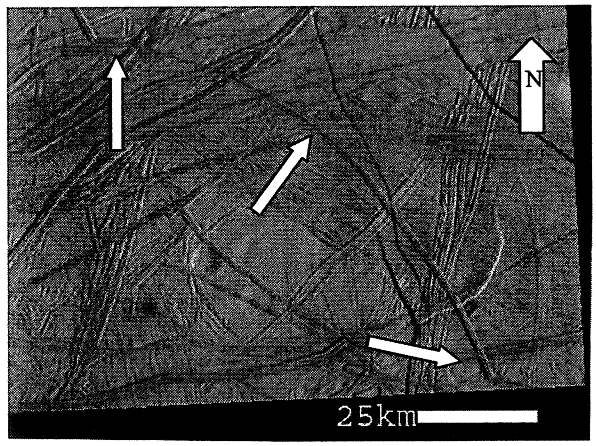

Figure 2. Arrows indicate a complex cycloid segment with changing morphology along strike. The NW end is a proto-ridge (using the nomenclature of [2]) and gradually changes towards the SE into a double ridge (image center ~ 21° N, 133° E).

Segment Morphology: Some cycloids change morphology along individual segments, usually with an abrupt change in morphology at the cusp of a segment followed by a gradual change along strike of the adjacent segment. Fig. 2 shows one such segment that is a well-developed double-ridge at its SE tip with a gradually changing morphology into a proto-ridge [2] towards its NW tip. This variability illustrates the notion that cycloids cannot always be defined by a single morphology, and may also imply that cycloid segments are subject to different loading conditions along strike.

Interpretation of Complex Segments. Previous work has modeled double ridge formation from shear heating [7], diurnal opening and closing [8], or linear diapirism [9]. The diapir model [9] does not address curved ridges, while the other two models [7,8] lead to differing interpretations of cycloids with complex morphologies. If double ridges form as the result of shear heating [7], one would expect double ridges to be more prominent in areas that have undergone more shear and less prominent in areas of less shear. If this model is accurate, the complex segment shown in Fig.

2 would have been subject to more shear near its SE tip and gradually less shear towards the NW. Conversely, if double ridges form as tension fractures that are re-worked by repeated diurnal opening and closing [8], the segment in Fig. 2 can be interpreted to have been subject to the most diurnal working in the SE and gradually less towards the NW.

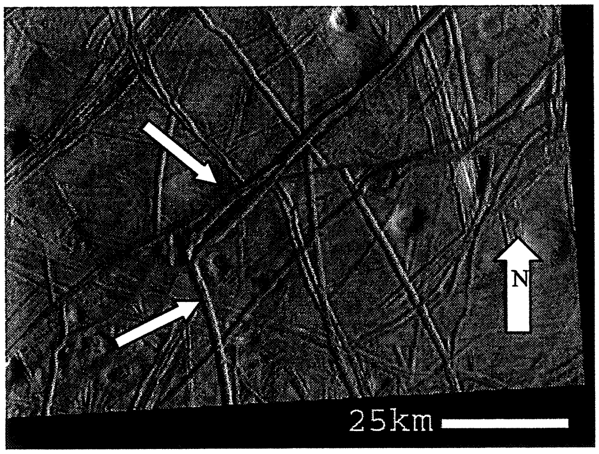

Figure 3. Arrows indicate a complex cusp where a segment from the south meets two segments from the northeast. The two northeast trending segments merge into one ridge towards the northeast (image center ~ 28°N, 140°E).

Cusp Morphology: Previous work has not detailed the styles and angles of cusps of cycloids. Many cycloids have cusps that are simple intersections between two segments (Fig. 2) while others are more complex (Fig. 3). There appears to be no characteristic angle (angles A and B in Fig. 1) between cycloid segments or dependence on trend direction of segments at cusps. Nonetheless, all measured angles are acute and typically fall between 50-70°. High resolution Galileo images (e.g. Fig. 3) have revealed that many cycloids have more complex cusps than what can be resolved at lower, Voyager-like resolutions. As described below, these complex cusps may provide insight into growth directions of similar cycloids, and hence their morphologic evolution in the tidal stress field.

Formation of Complex Cusps. We interpret complex cusps to form by secondary fracturing related to strike-slip motion on a pre-existing feature [e.g. 10,11]. According to the tidal walking theory [12], throughout one Europan day, a pre-existing crack is subject to an ever-changing stress field in which it will be subject to a repeating cycle of opening, sliding, closing and then frictional back-sliding. During the time when a crack is subject to shearing, it may develop secondary tensile fractures (also known as tail cracks, wing cracks, kinks, or horsetail fractures depending on their shape) in its extensional quadrants [5,10,13]. Tail cracks are predicted to form at about 70° to the trend of the crack for pure strike-slip sliding, but have been shown to form at lower angles for instances of mixed strike-slip/dilational motions [10]. This result agrees with the observation that cusp angles are commonly between 50-70°. Secondary fracturing, like that seen near the SE end of Agenor Linea [10,14], typically occurs as multiple fractures, but has also been shown to occur as a single secondary fracture [10,11]. If cusps form by utilizing secondary fractures created during the sliding portion of the diurnal cycle on pre-existing cycloid segments, it would not be unexpected for some cusps to be simple and some to be more complex. Complex cusps could potentially be used to infer growth direction of cycloids since the side of the cusp with multiple ridges would have formed as secondary fracturing and would thus be younger. Offsets may not be visible across cycloids since the amount of slip required to create secondary fracturing is much less than what can be resolved even in high resolution Galileo images.

Discussion: Based on the tidal walking theory, the northern hemisphere should be subject to right-lateral frictional back-sliding ("pure" strike-slip motion) on pre-existing lineaments. We thus interpret that in Fig. 3, the southern segment is oldest and the cycloid grew to the NE using multiple secondary fractures created during right-lateral motion during the tidal walking of the southern segment. This interpretation agrees with growth direction implied by the diurnal model which would also predict this northern hemisphere cycloid to grow in a counter-clockwise manner, however we present a slightly different, but compatible, mechanism for formation of cusps.

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